Performance of the RNG and Two-Layer k-ε Models in The Simulation of LWR Fuel-Bundle Flows

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The economic and safety performance of LWR fuel bundles is significantly affected by thermal mixing, which is driven by cross-flows and turbulence. Although no single existing turbulence model predicts a sufficiently wide range of flows with accuracy adequate for engineering needs, at this time for most flows the k-ε models seem to be the best choice. In Ref. 1 an assessment was presented of the standard high Reynolds (Re) number k-ε model, the quadratic high Re number k-ε model and the low Re number k-ε model. It was shown that there is a significant discrepancy between model predictions and experimental measurements. In this work, an assessment of the RNG k-ε model[2] and a two-layer k-ε model[3] is presented.

The RNG model is based on the renormalization group formalism of Yakhot and Orszag as discussed in Ref. 2. In the two-layer model, the "standard" k-ε model is applied everywhere except at near-wall flow regions where a low Reynolds number turbulence model is used. The grid structure near a wall is fine enough to resolve the boundary layer.

The available experimental information for the evaluation of turbulence models for the simulation of flows in reactor fuel bundles is very limited. In the mid-1970s a series of experiments were performed at Pacific Northwest Laboratories[4] to investigate turbulent flow phenomena in a model 7 x 7 fuel rod bundle consisting of 0.996-cm-diameter rods with a pitch of 1.369 cm. Axial components of the local mean velocity and local intensity of turbulence were measured using a laser Doppler anemometer. The experiments were performed in water at 29.4˚C and with Reynolds numbers of 1.4×10^4, 2.9×10^4, and 5.8×10^4. The important features of the flow were not significantly dependent on the Reynolds number, and in this work the experiment with a Reynolds number of 2.9×10^4 (inlet velocity of 1.74 m/s) was used as benchmark.

For this analysis, a commercial CFD code based on an unstructured grid was used. In this code, turbulence is simulated with a number of variants of the two-equations k-ε model. For advection a number of schemes are provided, including first-order upwinding, central differencing, combinations of first-order upwinding and central differencing, and a gradient-based total variation diminishing, second-order accurate scheme. In this work, the second order total variation diminishing scheme was used.

For this assessment a section of the fuel bundle, as shown in Fig. 1a, at the center of the bundle and away from spacer grids (where the effect of the spacers on turbulence has died out) was modeled. For the RNG model, the distance from the wall of the center of the computational cells adjacent to a wall was about $12y^+$, as recommended by the developers of the model. For the two-layer model, this distance was about $1y^+$, and the near-wall region where the low Re number model was applied, was represented by fifteen cells covering a distance from the wall of about $50y^+$. For the RNG model, on a plane perpendicular to the main flow direction there were 792 cells. For the two layer model, on the same plane there were 2640 cells. The simulations were performed on eight processors of a Linux cluster, and were run as steady-state problems. The predictions are the result of the solution of the 3-D Navier-Stokes equations and of the k-ε equations, without the use of any correlations beyond those used in a k-ε model.

Comparisons of code predictions with measurements were made for the turbulence intensity (local fluctuating axial velocity over local axial velocity) and the axial velocity (local velocity/average velocity) at points on the axis of symmetry of the model (see Fig. 1a) and on a plane perpendicular to the direction of the main flow. The measurement error for the velocity is ±11% and for the turbulence intensity ±16%.

Because a k-ε model does not provide information to directly compute the turbulence intensity, in Ref. 1 the assumption was made that the contribution to turbulent kinetic energy of the fluctuations of the lateral components (perpendicular to main flow direction) of velocity is negligible. This overestimated the discrepancy between predictions of the turbulence intensity in the main flow direction and experimental measurements. LES simulations of the experiment analyzed here show that the fluctuations of the velocity component in the main flow direction contribute about 60% of the total turbulent kinetic energy. In this work, the turbulence intensity in the main flow direction was computed from

$$\frac{(u_f^2)^{1/2}}{\bar{u}}=\frac{(0.6\times 2k)^{1/2}}{\bar{u}}$$

where: u_f = fluctuating velocity, $\bar{u}$ = mean local velocity, and k = turbulent kinetic energy

Figures 2a and 2b show axial velocity and turbulence intensity predictions and measurements. For comparison are also shown predictions of the standard high Re number k-ε model. For the standard k-ε model the same grid was used as for the RNG model. All k-ε models predict very nearly the ame velocity profile. There is an overprediction around the center of the flow channel (area of velocity peaks) and an underprediction in the gap between the rods (area of velocity dips). The maximum discrepancy between predictions and measurements is about 8%, well within the experimental error. All k-ε models overpredict the turbulence intensity, especially in the region around the gap. The predictions of the RNG and standard k-ε model are nearly identical, while those of the two-layer model are significantly higher. The maximum overprediction of the RNG and standard k-ε models is about 23%.

In conclusion, this analysis shows that although the k-ε models predicted the distribution of the mean velocity quite well, they significantly overpredicted the turbulence intensity. Because turbulence enhances thermal mixing, better turbulence models are needed for an accurate prediction of thermal mixing and optimization of system performance.

References

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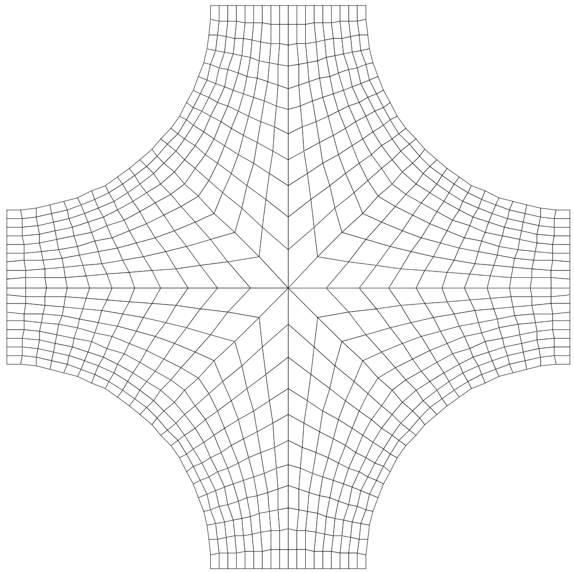
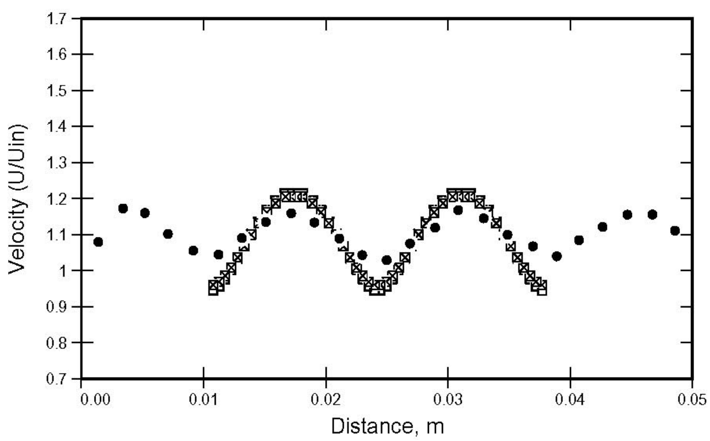


(a)



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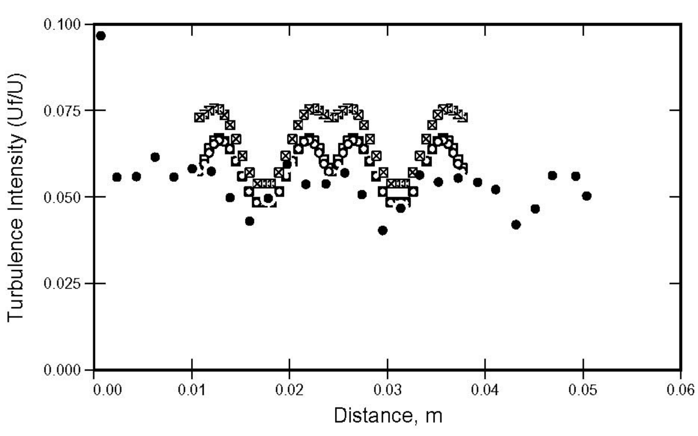

(c)

Figure 1. Velocity and Turbulence Intensity: ● experiment, ○ standard, □ RNG, ⊠ Low Re.